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Automated Assessment of Ultimate Longitudinal Strength of Ship Hulls

M.J. Smith
N.G Pegg

Defence R&D Canada

DEFENCE RESEARCH ESTABLISHMENT ATLANTIC

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November 2000

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Abstract

An automated approach to ultimate strength assessment of ships using DREA's ultimate strength analysis suite is described. The analysis suite improves the ability to perform timely ultimate strength assessments of warships by providing access to UK and Canadian analysis codes and databases under a single user interface. The interface also allows for automatic cross-sectional model generation from three-dimensional ship finite element models with the MGDSA programme. A step-by-step description of the analysis options and procedures is provided, from the generation of sectional models to the viewing of results. Ultimate strength results obtained with the suite are presented and compared for three Canadian vessels. Based on these results, recommendations are made for the most effective use of the analysis suite and for its future improvement.

Résumé

Le présent document décrit une approche automatisée à l'évaluation de la résistance à la rupture des navires au moyen du progiciel d'analyse de la résistance à la rupture du CRDA. Ce progiciel permet d'effectuer plus facilement des analyses opportunes de la résistante à la rupture de navires de guerre en regroupant l'accès aux codes d'analyse et aux bases de données du Royaume-Uni et du Canada en une seule interface utilisateur. L'interface permet aussi de produire automatiquement des modèles en coupe transversale à partir de modèles à éléments finis tridimensionnels grâce au programme MGDSA. Une description étape par étape des possibilités et des méthodes d'analyse est fournie, de la production de modèles en coupe au visionnement des résultats. Les résultats des analyses de la résistance à la rupture de trois navires canadiens obtenus au moyen du progiciel sont présentés et comparés. En fonction de ces résultats, des recommandations sont faites sur la façon la plus efficace d'utiliser le progiciel et sur la façon de l'améliorer.

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Executive summary

Introduction

Ultimate strength analysis is undertaken to find the bending load that will cause the collapse of a ship's hull. Accurate knowledge of this is essential to determine a ship's weight limit and allowable operating conditions. Martec Limited of Halifax Nova Scotia, under contract to DERA Rosyth and DREA, has recently completed a project entitled 'Incorporation of UK NS94 Ultimate Strength Analysis in MGDSA'. Under this contract, UK and Canadian computer codes for ultimate strength analysis have been integrated into a single software application with a common user interface and a common database, referred to here as ULTSAS (ULTimate Strength Analysis Suite). In addition, cross-sectional models used as inputs to the ultimate strength codes can now be generated automatically from existing finite element ship structural models. In all, ULTSAS has significantly increased the speed at which ultimate strength assessments can be performed.

Principal Results

This Technical Memorandum describes the theory, and demonstrates the effective use of ULTSAS, first by describing the analysis capabilities and procedures, and second by presenting results obtained from analysis of real ships. To this end, an informal step-by-step guide to the use of ULTSAS is given, from the automated generation of a cross section to the viewing of the results. Following that, the results of the various ultimate strength analysis codes are examined through detailed comparison of three Canadian vessels. These results serve to illustrate the prominent features of the analysis codes. This leads directly to a series of recommendations to guide the user in the most effective use of the ULTSAS.

Significance of Results

Automated evaluation of ultimate strength is an essential component of the ongoing Improved Ship Structural Maintenance Management (ISSMM) project. The results of this study directly pertain to how ULTSAS is to be customised for use in the ISSMM Software Tool (IST). Most importantly, it is shown that reliable results can be efficiently obtained with the analysis suite in its present form. ULTSAS can be used to undertake an ultimate strength assessment in a matter of minutes if a finite element model of the ship already exists. This is a considerable increase in efficiency over previous efforts, which required several hours.

Smith, M. J., Pegg, N. G. (2000). Automated Assessment of Ultimate Longitudinal Strength of Ship Hulls. (TM 2000-143). Defence Research Establishment Atlantic.

Sommaire

Introduction

L'analyse de la résistance à la rupture sert à déterminer la charge de flexion qui entraîne l'affaissement de la coque d'un navire . Il est essentiel de connaître la charge de flexion exacte pour pouvoir déterminer la charge limite du navire ainsi que les conditions d'utilisations permises. Martec Limited de Halifax Nouvelle-Écosse, en vertu d'un contrat avec DERA Rosyth et le CRDA, a terminé récemment un projet intitulé « Intégration du système d'analyse de la résistance à la rupture NS94 du Royaume-Uni au MGDSA ». Dans le cadre de ce projet, les codes informatiques d'analyse de la résistance à la rupture du Royaume-Uni et du Canada ont été intégrés en une seule application logicielle (interface utilisateur unique et base de données unique) appelée ULTSAS (Progiciel d'analyse de la résistance à la rupture). Les modèles en coupe transversale qui ont servi à l'entrée des codes de résistance à la rupture peuvent maintenant être produits automatiquement à partir des modèles structuraux de navires à éléments finis existants. ULTSAS a donc permis d'augmenter de manière significative la vitesse d'exécution des évaluations de la résistance à la rupture.

Principaux résultats

La présente note technique traite de la théorie derrière ULTSAS et de son utilisation en décrivant les capacités et les méthodes d'analyse et en présentant les résultats obtenus suite à l'analyse de navires réels. Un guide point par point officieux sur l'utilisation de ULTSAS explique le processus, de la production automatisée d'une coupe transversale au visionnement des résultats. Les résultats des divers codes d'analyse de la résistance à la rupture sont ensuite examinés au moyen d'une comparaison détaillée de trois navires canadiens. Ces résultats permettent d'illustrer les principales caractéristiques des codes d'analyse. Viennent ensuite une série de recommandations visant à aider l'utilisateur à exploiter ULTSAS de la façon la plus efficace possible.

Signification des résultats

L'évaluation automatisée de la résistance à la rupture est une composante essentielle du projet de Gestion améliorée de la maintenance de la structure des navires (GAMSN). Les résultats de la présente étude portent directement sur la façon dont ULTSAS doit être adapté pour être utilisé dans l'outil logiciel de la GAMSN. Plus important encore, il a été démontré qu'il était possible d'obtenir des résultats fiables de façon efficace avec le progiciel d'analyse dans sa forme actuelle. Grâce à ULTSAS, il est possible d'effectuer une évaluation de la résistance à la rupture en quelques minutes si un modèle à éléments finis du navire existe déjà. Cela constitue une nette amélioration du point de l'efficacité par rapport aux systèmes précédents qui exigeaient plusieurs heures.

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1. Introduction

Ultimate strength analysis is undertaken to find the bending load that will cause the collapse of a ship hull. Accurate knowledge of this is essential to determine a ship's weight limit and allowable operating conditions. Defence research organisations in various countries have developed specialised computer codes for evaluating ultimate strength (ULTMAT in Canada [1], FABSTRAN/NS94 in the UK [2-4], and ULTSTR in the US [5]).

Martec Limited of Halifax Nova Scotia, under contract to DERA Rosyth and DREA, has recently completed a project entitled 'Incorporation of UK NS94 Ultimate Strength Analysis in MGDSA'. Under this contract, the technical aspects of which are described in a series of three reports [6-8], the UK and Canadian ultimate strength codes have been integrated into a single software application with a common user interface and a common structural database. The user interface together with the analysis codes will be referred to here as ULTSAS (ULTimate Strength Analysis Suite).

Another aspect of the contract involved developing capabilities in the finite element-based ship structure analysis tool MGDSA [9] for automatically generating cross-sectional ultimate strength models from three-dimensional finite element meshes of ships structures. These automatically generated cross sections are made available to ULTSAS in a standard format. This facility, in combination with the common user interface and common database, has significantly improved the speed at which ultimate strength assessments can be performed.

The purpose of the present study is to illustrate the use of ULTSAS, first by describing the analysis capabilities and procedures, and second by presenting results obtained from analysis of real ships. To this end, Section 2 gives an informal step-by-step guide to the use of ULTSAS, from the generation of a cross section with MGDSA to the viewing of results. Section 3 presents and compares results obtained for three Canadian warships. These results include moment-curvature plots for vertical bending and interaction curves for bi-axial ultimate strength. Based on these, several recommendations are provided to guide the user in the effective use of the analysis suite and to suggest future improvements.

2. Ultimate Strength Analysis

2.1 Methods and Analysis Codes

The term 'ultimate strength' has been used in different contexts for ship structures. It has been used to describe almost any failure mechanism involving buckling or collapse of the main hull girder or its components. In this study, ultimate strength will be defined as the maximum bending moment resistance of the ship hull girder structure. Ultimate strength is generally determined at several longitudinal positions, the most significant being amidships where bending loads are the greatest. Figure 1 shows an example of a symmetric half section of a ship under an ultimate strength failure from a sagging load where the deck plate is failing in compressive buckling and the bottom structure is in tension.

Figure 1: Example of Ship Cross Section Undergoing a Sagging Ultimate Strength Failure

Two programs, ULTMAT [1] and FABSTRAN/NS94 [2-4], have previously been used for hull girder ultimate strength calculations in DND. The geometry of the cross section of interest and the elasto-plastic axial deformation characteristics of individual stiffened plate components that make up the cross section are required for these programs. The elasto-plastic characteristics of the individual stiffened plate components can be generated from non-linear finite element analysis or possibly other numerical approaches and test data.

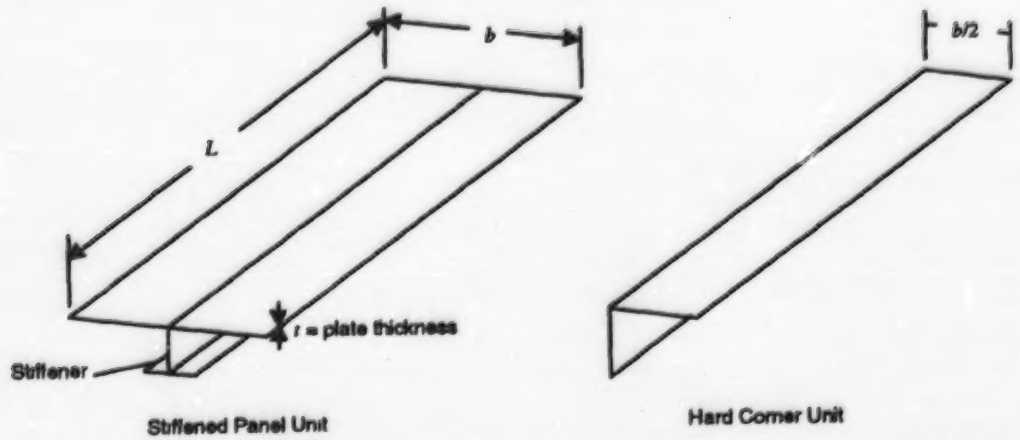


Figure 2: Typical Longitudinal and Hard Corner Structural Units Used in the Smith Method

Both ULTMAT and FABSTRAN/NS94 use an approach credited to Smith [3] that allows for the modelling of the progressive collapse of a ship hull under moment loading. It is a simplified approach in which only a cross section of the ship is modelled. The cross section is divided into small, independently acting units, two of which are shown in Figure 2. Each unit is comprised of either a stiffener or a corner node (two or more plates meeting at an angle) and its associated plating, and has a length equal to the distance between transverse frames. No deformation of the transverse frames is permitted.

The rationale for the Smith method lies in the behaviour of a ship section under a bending-induced collapse. On the compression side, load shedding occurs in the plating between the longitudinal stiffeners until nearly all the load is being carried by the stiffeners, and very little is being carried by the plating. At collapse, the stiffeners and their associated plating act essentially like independent beam-columns. On the tension side, the plating and stiffeners are assumed to maintain the original cross-sectional shape under the assumption that plane sections remain plane.

Since each unit is assumed to act independently, each has its own load-carrying characteristics. It can carry a certain amount of flexural buckling stress when subjected to compressive force, or yield stress when subject to tensile force. Two major strength-reduction factors, initial imperfections and residual stresses, are considered through modification of the load-carrying characteristics of each individual structural unit. Typical load-carrying characteristics for compressive stiffened panels are shown in Figures 3 and 4 as normalised averaged stresses and strains in the longitudinal direction. The two plots show respectively the effects of welding-induced geometric imperfections and residual stresses.

After the load-carrying curves of each unit are known, the neutral axis of the cross section can be obtained by equilibrium of the axial force. The moment can be determined by the summation of the force in each unit times its distance to the neutral axis.

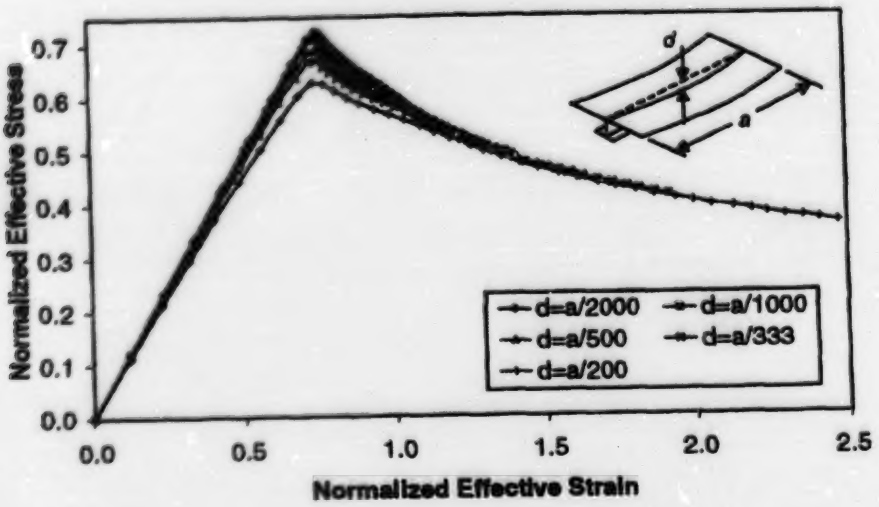


Figure 3: Normalised Stress-Strain Curves for Various Levels of Geometric Imperfection (from Reference [10])

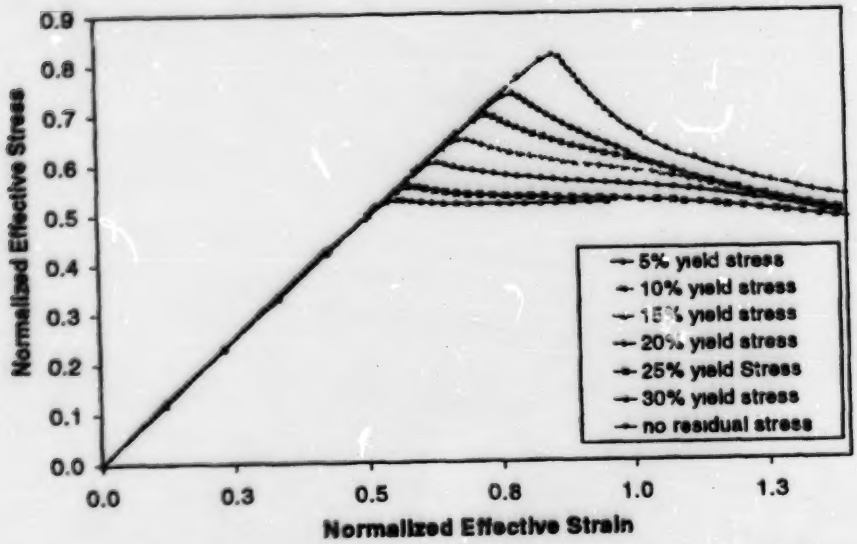


Figure 4: Normalised Stress-Strain Curves for Various Levels of Residual Stress (from Reference [10])

ULTMAT is a DREA developed code which automatically divides the cross section into units and assumes each compressive stiffened panel unit buckles about an axis perpendicular to the stiffener and in the plane of the plating. Load-displacement data for the individual structural units is taken from an existing database or generated through non-linear finite element analysis if it does not exist in the database. The version of ULTMAT currently included in ULTSAS permits moment-curvature and ultimate strength calculation for hog and sag loading (vertical bending) only.

The FABSTRAN/NS94 software system includes PREFAB, FABSTRAN, POSTFAB and NS94A, NS94B, NS94C and NS94D. FABSTRAN (Frame And Beam Static and Transient Response Analysis) is the main program used to obtain the response characteristics of each unit. This program is a non-linear two-dimensional beam finite element program with built-in plate buckling information which produces the effective stress-strain or load-deformation curve for the stiffener-plate unit. These curves are called 'load-shortening curves' (LSC) in FABSTRAN. By combining the load-shortening curves for each unit into the geometric information of the hull cross section, the NS94 programs calculate the full moment-curvature relationship for the cross section from which the ultimate moment capacity can be derived. The NS94 programs are similar but differ in that NS94A calculates vertical bending response only using FABSTRAN generated LSCs. NS94B uses FABSTRAN curves but calculates bi-axial bending response. NS94C calculates vertical bending response only but uses a predetermined generic LSC database, while NS94D calculates the bi-axial bending response with the generic LSC database.

2.2 Introduction to ULTSAS

DREA, in conjunction with Martec Limited of Halifax, Nova Scotia, have been developing a suite of structural analysis codes entitled MGDSA (MAESTRO Graphics Detail Stress Analysis). MGDSA was originally created to provide a means to undertake detail finite element stress analysis in conjunction with the global ship hull structural analysis program MAESTRO [11]. The MGDSA code has become popular with MAESTRO users, resulting in numerous other features and analysis options being added to the code since its inception. Under a co-operative agreement with the U.K. MOD DERA (Defence Evaluation and Research Agency), DND sponsored development of an ultimate strength analysis application module for MGDSA. This is also intended for use in the ISSMM [12] project.

ULTSAS uses the DREA code ULTMAT and the DERA codes FABSTRAN/NS94 described in the previous section. Links to non-linear FEA through VAST [13] and ASAS-NL [14] are also provided. The integration of the analysis codes under a single user interface, and the ability to generate cross-sectional models automatically from three-dimensional finite element models, have significantly increased DREA's capabilities in ultimate strength assessment. Previously, cross-sectional models had to be developed directly from drawings using a digitising tablet. The cross-sectional data then had to be manually adjusted to the format of a given analysis program. Now, with ULTSAS, the modelling of single cross section, which previously may have taken several hours, can be done in a matter of minutes provided a three-dimensional finite element model of the ship already exists.

The following subsections illustrate the application of ULTSAS through the ultimate strength

module in MGDSA.

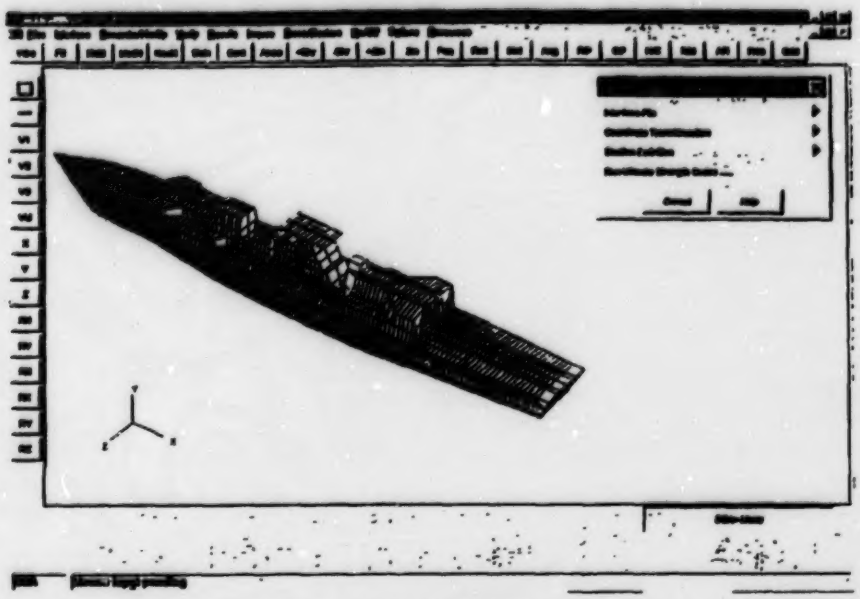


Figure 5: MGDSA Operating Shell with MAESTRO Global Model of the HALIFAX Class

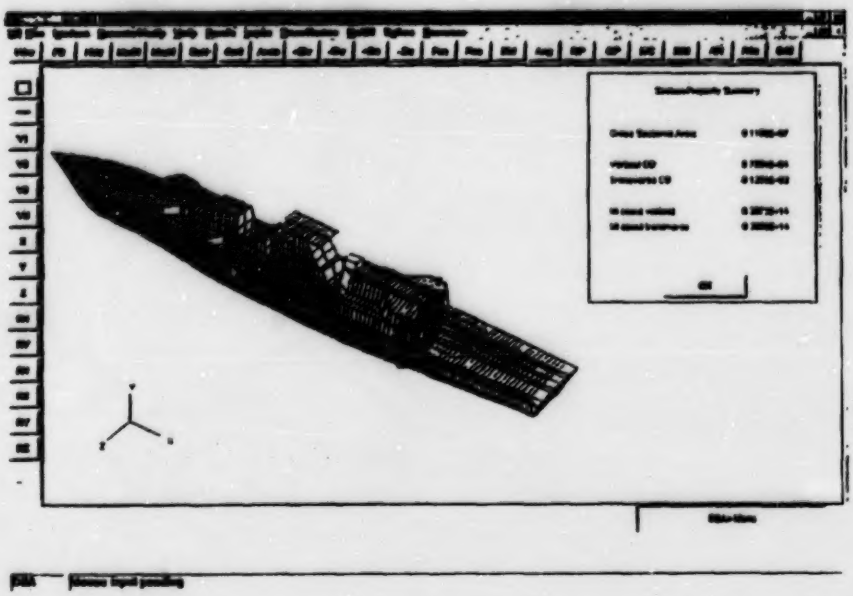


Figure 6: A Cross Section Selected from the HALIFAX Class MAESTRO Model.

2.2.1 Generating the Hull Cross Section with MGDSA

Figure 5 shows the MGDSA operating shell with a MAESTRO global finite element (FE) model of the HALIFAX class frigate. The pull-down menu for the ultimate strength application is shown in the figure. Global models from other FE programs can also be used for this starting point. Analysis proceeds by identifying the cross section in the global model for which ultimate strength analysis is required (Figure 6). Identification is done interactively with the screen cursor or by identifying the axial co-ordinate of the section. The cross-section information is saved from MGDSA to a file with extension 'usd'.

2.2.2 Importing a Cross Section into ULTSAS

Once the cross-section file has been created by MGDSA, the ULTSAS interface is launched and the user first creates a new project in the user-interface application. The next dialog to be encountered is shown in Figure 7, which allows the user to specify the origin of the cross-sectional definition. The user can specify that cross sections be read in either the MGDSA-generated 'usd' or the DIGFEM format. (DIGFEM is a programme developed at DREA to create cross-sectional models directly from drawings using a digitising tablet.)

The user is then provided with analysis options including the type of analysis, the analysis programme, and the load-shortening curve database to be used, through the dialog shown in Figure 8. Three choices of load shortening curve database are provided. The two VAST databases are derived from non-linear finite element analysis of stiffened panels in the HALIFAX class frigate. The end-to-end database uses stiffened panels extending from one frame to another, whereas the centre-to-centre database uses models spanning the mid-frame positions. The NS94D database is comprised of simple bi-linear curves describing the collapse of generic stiffened panels. They are not specific to a particular class of vessel.

All the LSC databases contain collapse curves of stiffened panels for a range of plate and stiffener sizes. The size of any given stiffened panel is determined by the slenderness ratio for plating between stiffeners, β, and the slenderness ratio of a longitudinal stiffener, λ. Formulas for β and λ are given by the following:

$$\beta = (b/t)(\sigma_y/E)^{1/2} \qquad \lambda = (L/\pi r)(\sigma_y/E)^{1/2}$$

in which b is the total width of the plating, t is the plate thickness, E is the elastic modulus, σ_y is the yield stress of the material, L is the length of the panel, and r is the radius of gyration of the stiffener and its associated effective plating combined. The analysis programs determine β and λ values for a given stiffened panel. An appropriate LSC for the panel is then determined by interpolating from curves associated with the nearest values of β and λ in the database.

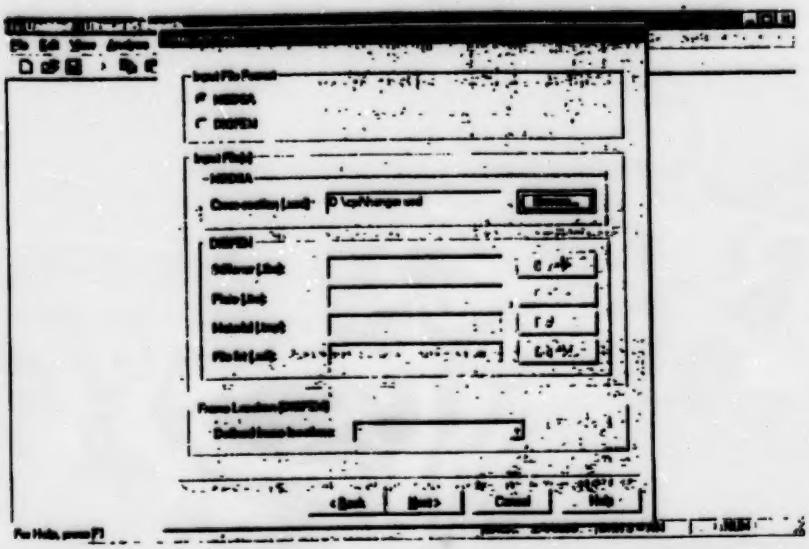


Figure 7: Importing an MGDSA Cross Section to the Ultimate Strength Application

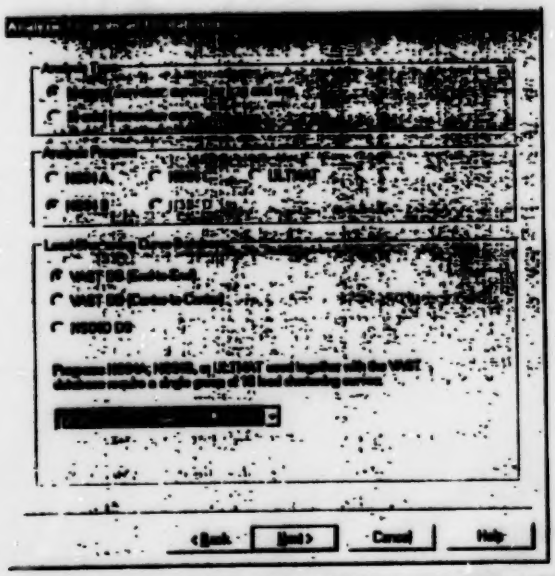


Figure 8: Analysis Options for Ultimate Strength Analysis

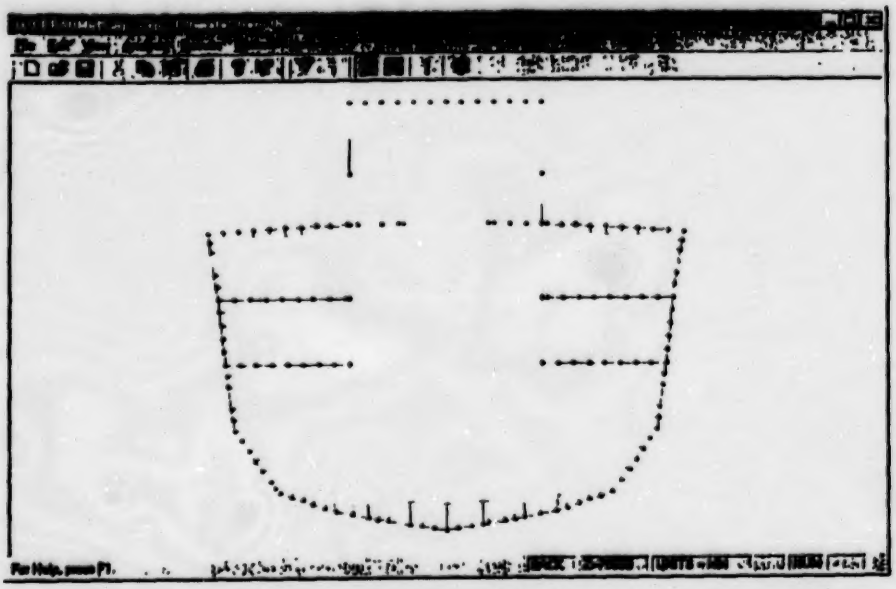


Figure 9: Ultimate Strength Cross Section Viewed in 'Finite Element' Mode

2.2.3 Viewing the Cross Section in 'Finite Element' Mode

The cross section is first presented to the user in the 'finite element' mode (Figure 9), which allows individual plates and beam stiffeners to be accessed and edited with a mouse. When plates or stiffeners are selected, dialogs appear for modifying dimensions, defining material properties and applying corrosion damage or geometric imperfections. The dimensions and material properties are carried over from the global model, but the user may need to adjust these to include information on individual plate and stiffeners not present in the global model. These dialogue boxes allow the user to change this information. Figures 10 and 11 show the dialogue boxes for modifying plate and stiffener properties, respectively.

2.2.4 Viewing the Cross Section in 'Structural Unit' Mode

The alternative way to view the cross section is in 'structural unit' mode (Figure 12). In this mode, individual stiffened panels and hard corners can be selected and modified. Dialog boxes for modifying longitudinal stiffened panels and hard corners are shown in Figures 13 and 14, respectively. As can be seen, the program automatically provides a load-shortening curve from the database that is deemed to be the most appropriate for the dimensions of the structural unit. The user can at this point change the load shortening curve to another from the database, or can generate a new one with finite element analysis. The latter procedure has been automated for use with the FABSTRAN and VAST finite element codes, so that a new curve is generated literally with the push of a button.

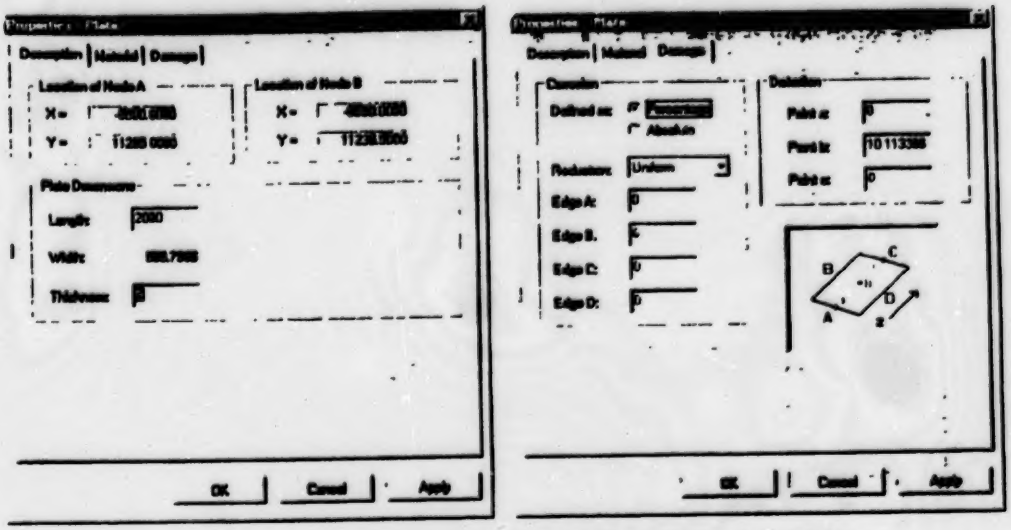


Figure 10: Dialogue Boxes for Modifying Plate Properties

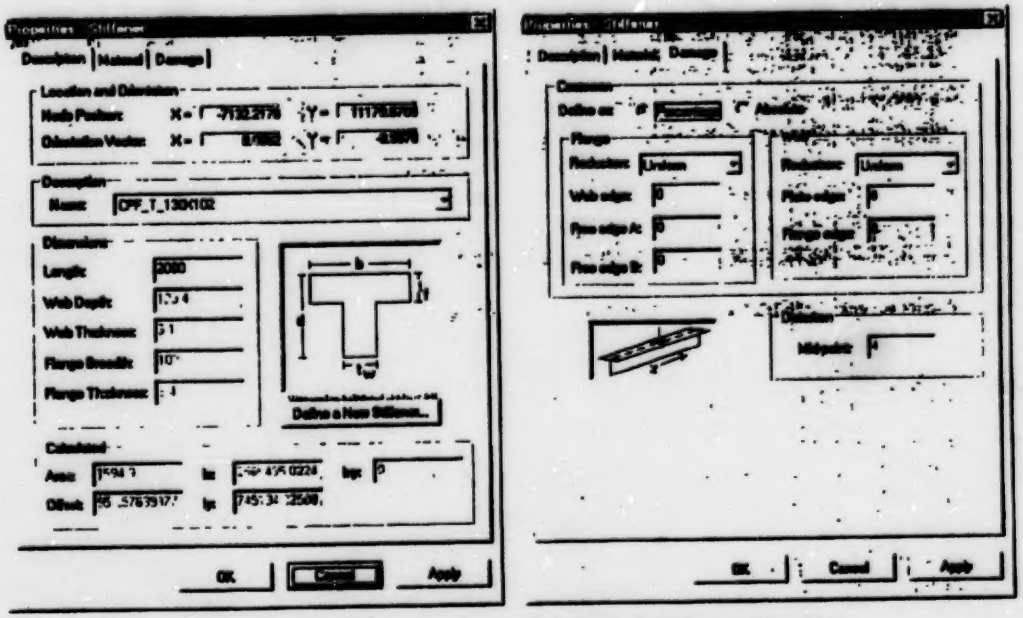


Figure 11: Dialogue Boxes for Modifying Stiffener Properties

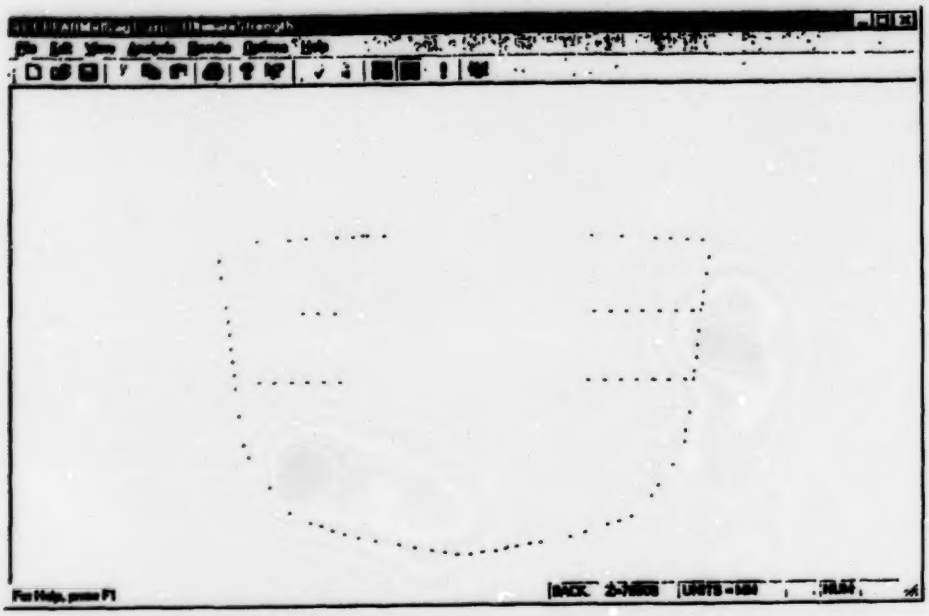


Figure 12: Ultimate Strength Cross Section Viewed in 'Structural Unit' Mode

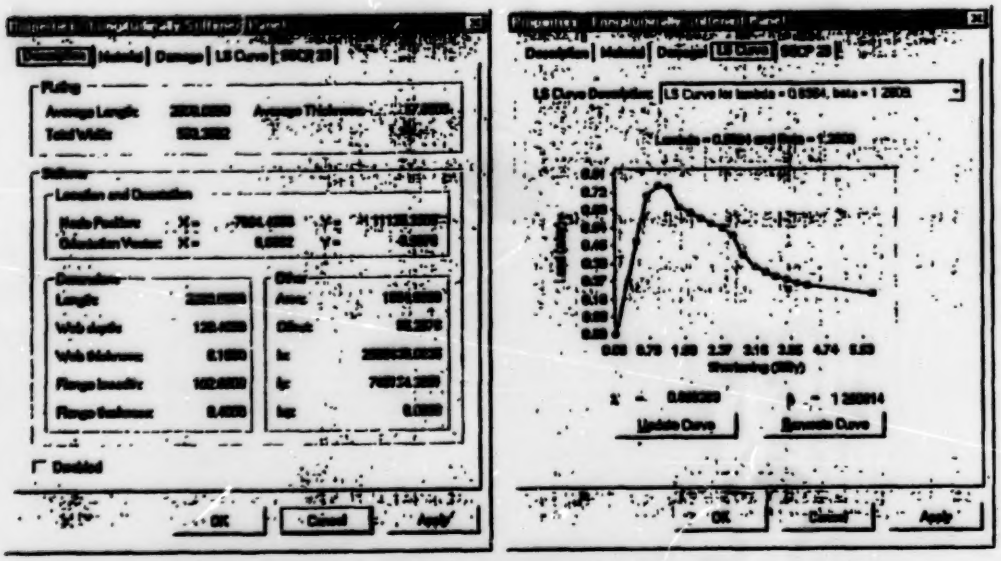


Figure 13: Dialogue Boxes for Modifying Stiffened Panel Properties

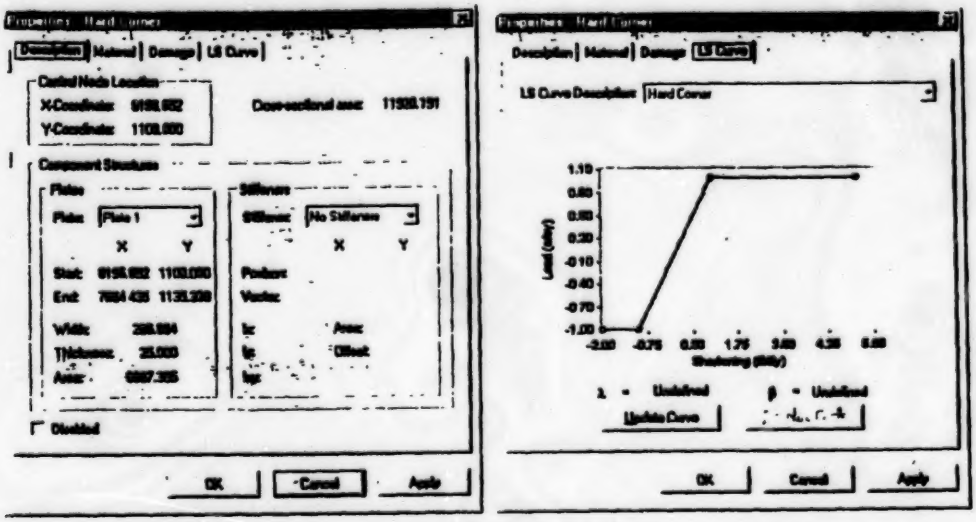


Figure 14: Dialogue Boxes for Modifying Hard Corners Properties

At this point the user can also remove any structural units deemed to be ineffective for ultimate strength analysis (e.g., structure which is not continuous over any significant length of the hull or superstructure, such as that indicated by dashed lines in Figure 12). This is done by selecting the 'Disabled' box on the 'Description' panel, as shown in Figures 13 and 14.

2.2.5 Performing an Ultimate Strength Analysis

Once the user has completed reviewing and modifying the cross-section properties, the ultimate strength analysis is undertaken. Two different types of analysis are available to the user: moment-curvature evaluation for vertical bending, and bi-axial ultimate moment evaluation (see Figure 8). The result for a moment-curvature evaluation is a moment-curvature graph like the one in Figure 15, which identifies the hog and sag branches of the vertical bending curve. The result for bi-axial ultimate moment evaluation is an interaction curve like the one shown in Figure 16.

The user can also graphically review the limit states for three different failure modes of the stiffened panels. Figure 17 shows plots of the limit states in a typical cross section in all three failure modes: elastic buckling, tripping of the longitudinal stiffeners, and yielding. In these plots the colour scale indicates the average stress level (in MPa) in each stiffened panel at which the given failure mode is predicted to occur. The limit states for buckling and tripping are determined in ULTSAS using the SSCP23 standard [15]. The limit state for yielding is simply the yield stress of the material.

Limit states are useful in that they show the relative strength and weakness of the individual stiffened panels. The lowest of the three limit state values indicates the probable failure mode for that particular panel. The complete limit state analysis would involve comparing these

values to the applied stress from a given design load. This feature, with the aid of stress analysis in MGDSA will be incorporated in later phases of the programme.

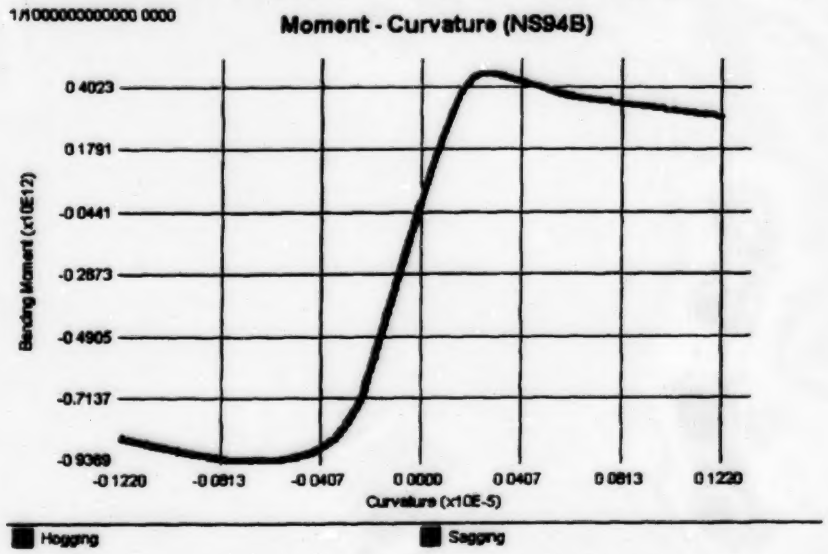


Figure 15: Example Moment Curvature Graph for Vertical Bending

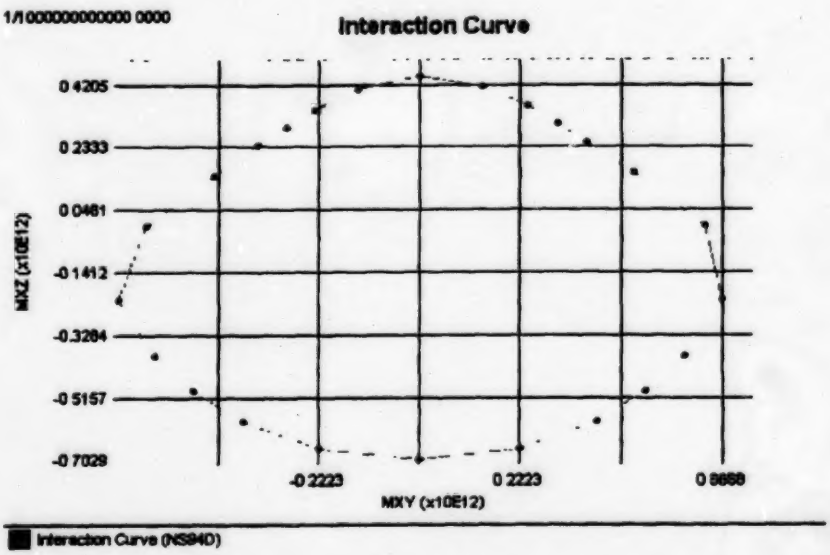
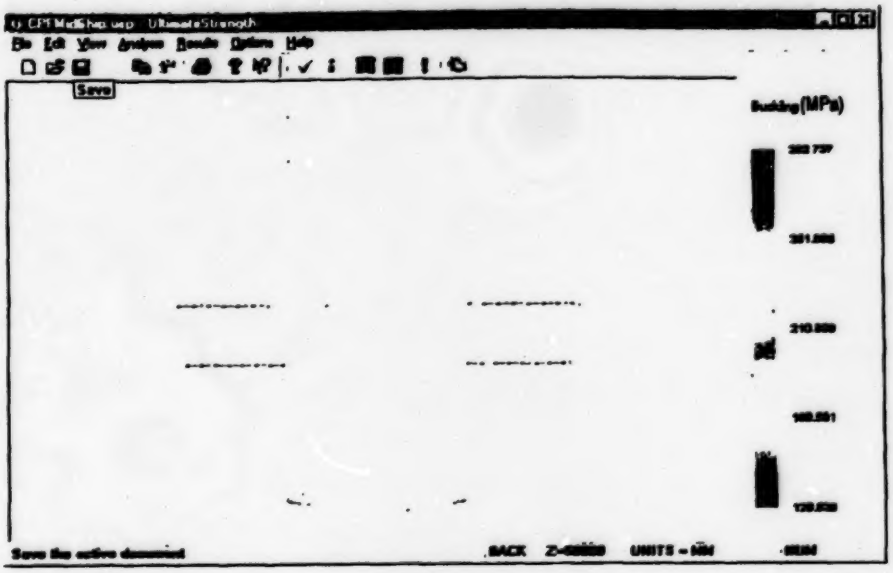
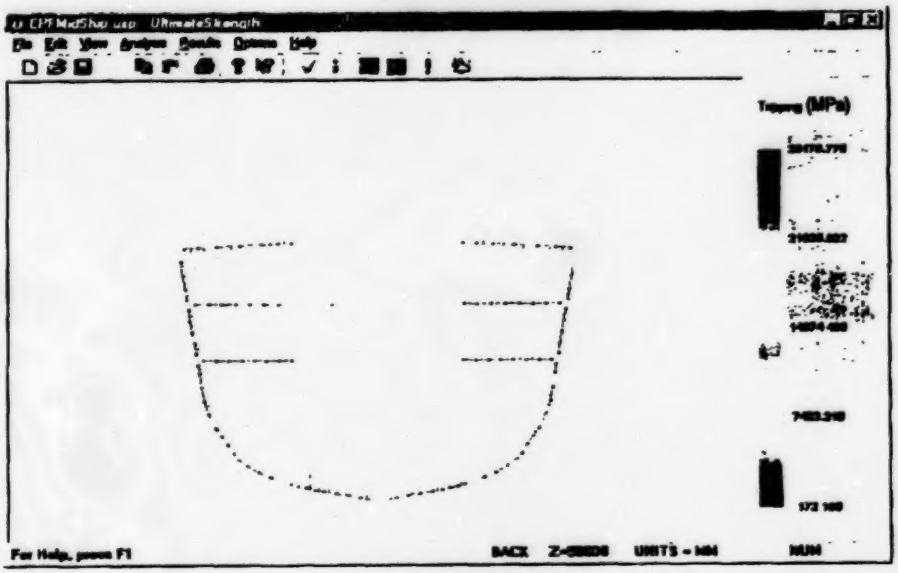


Figure 16: Example Ultimate Moment Interaction Graph for Bi-axial Bending

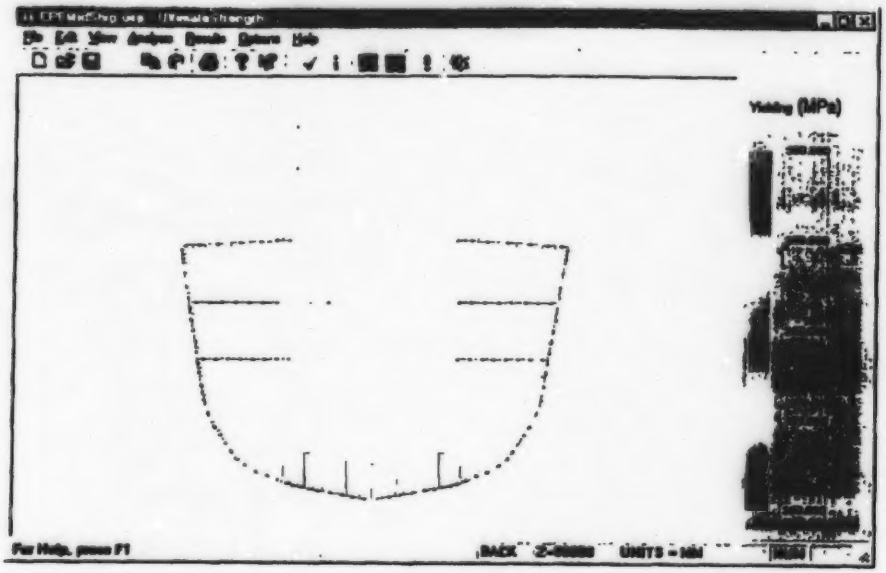


(a) Elastic Buckling



(b) Tripping

Figure 17: Graphical Display of SSCP23 Limit States



(c) Yielding

Figure 17: Graphical Display of SSCP23 Limit States (Cont'd)

3. Comparison of Ultimate Strength Assessments for Canadian Forces Vessels

As a way of demonstrating the use of ULTSAS in MGDSA, strength assessments of three CF vessels (the HALIFAX class, ANNAPOLIS class and a concept design for the proposed Afloat Logistics Support Capability (ALSC) vessel) are presented in this section . Moment-curvature plots for vertical bending and bi-axial interaction curves are compared for various combinations of the analysis programs (NS94A/B/C/D and ULTMAT) and the load-shortening curve databases (NS94C/D generic database and VAST databases). Based on these comparisons, recommendations are made for the most effective use of the ultimate strength suite.

3.1 HALIFAX Class

The ultimate strength of the HALIFAX class vessel has been assessed previously using the ULTMAT and the NS94 programs. The intention in this study is simply to demonstrate the options available to the user in the ultimate strength suite, and not to discuss the implications of the results on the strength of the vessels.

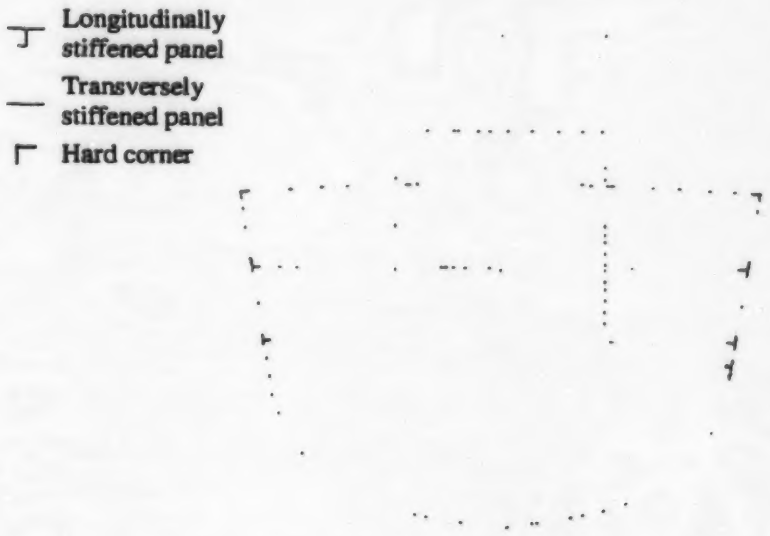


Figure 18: Amidships Cross Sectional Model of the HALIFAX Class

The cross-sectional model used in this case is shown in Figure 18, which was created from the MAESTRO 3D finite element model (Figure 5) near amidships. The cross section is shown in structural units mode, with the longitudinally stiffened panels in blue and the hard corners in black. Structural units drawn with broken lines have been deactivated for the purposes of the analysis. The length of each unit (in the direction of the longitudinal axis) is determined by the local frame spacing, since frames are assumed to be effectively rigid in an ultimate strength analysis. To model the actual framing arrangement in the HALIFAX class, the structural units have been adjusted so that those below the lowest (No. 2) deck are one metre long, and all others are two metres long.

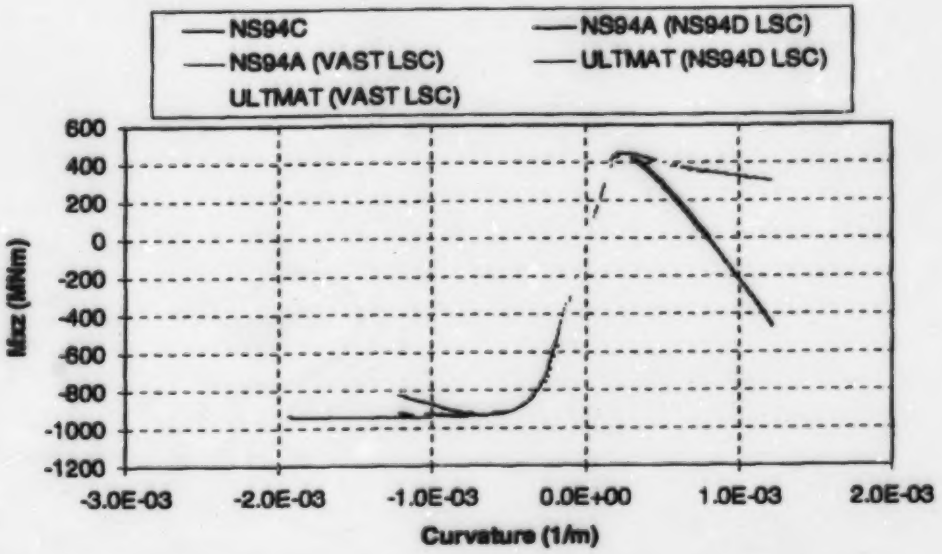


Figure 19: Amidships Vertical Moment-Curvature Plots for HALIFAX Class

Moment-curvature plots for vertical bending are shown in Figure 19, in which both hog and sag conditions have been combined in each of the five curves. Results from NS94A, NS94C, and ULTMAT are compared here in the pre- and post-collapse range in both hog and sag. Hog loading occurs for curvature values less than zero, and sag loading for curvatures greater than zero. Overall, the hull shows a greater tendency to collapse in sag (with the main deck in compression) than in hog. The hog ultimate strength at this section is about twice the sag strength. This is consistent with the half-framing in the lower half of the hull which greatly reduces the risk of buckling of panels in that region.

Two sets of results are obtained with NS94A and ULTMAT: one with the NS94D LSC database and the other with the VAST end-to-end LSC database. By default, NS94C uses the NS94D LSC database. A significant discrepancy in the results occurs in the post-collapse range, due to differences in the LSC databases. This is especially noticeable for sag loading. The generic NS94D database, which consists of simple, bi-linear curves extrapolated from the collapse limit, tends to underestimate the strength in the post-failure region. Conversely, the VAST LSC data, which are calculated with non-linear FEA over the whole range of loading,

retain a higher level of accuracy in the post-failure region. It should be noted that the choice of LSC database has no effect on the ultimate bending moment values in either hog or sag. It only affects the post-ultimate moment behaviour.

Figure 20 gives a comparison of interaction curves obtained with NS94B and NS94D, where Mxy is the horizontal bending moment and Mxz is the vertical bending moment. Two different curves are obtained with NS94B according to whether curvature or moment incrementing is used. In curvature incrementing the ratio of vertical to horizontal curvatures is held constant when an ultimate bi-axial moment is being evaluated. Conversely, in moment incrementing the ratio of vertical and horizontal bending moment is held constant during the analysis. NS94B allows both types of incrementing but defaults to curvature incrementing when accessed from ULTSAS. NS94D allows moment incrementing only.

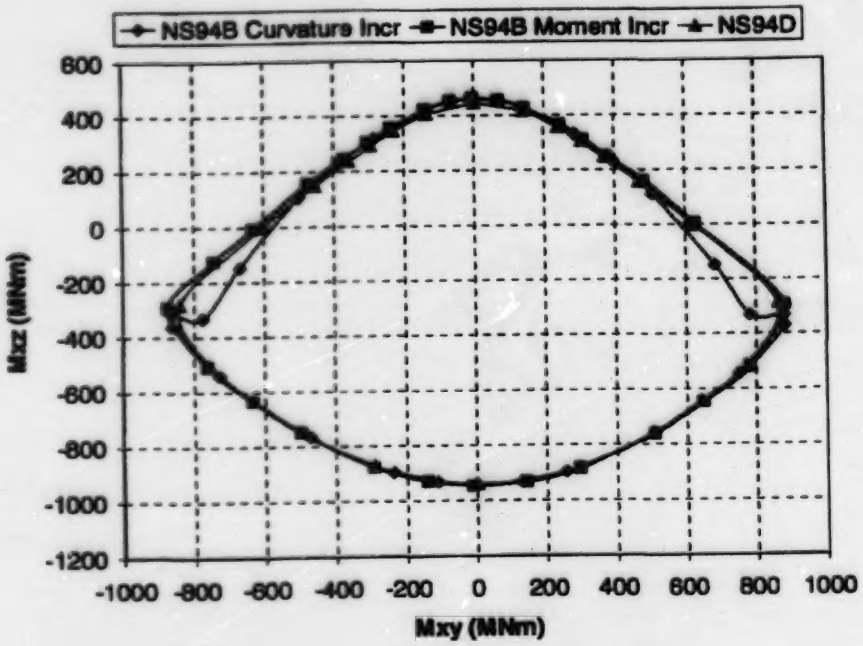


Figure 20: Bi-Axial Interaction Curves for HALIFAX Class at Midships

Significant differences arise for the NS94B curvature incrementing analysis when horizontal bending moments are applied. These take the form of cusps or 'ears' on the sides of the interaction curve. To determine the cause of this, the three interaction curves were examined in more detail.

Figure 21 shows the interaction curve for NS94B and curvature incrementing, with trace lines for each data point appearing in grey. The trace lines represent the values of the Mxy, Mxz pair as the section is loaded to failure. From these it is clear that the ratio of the moments does not in general remain constant during each analysis cycle, and that the ratio of the moments at

failure can differ greatly from the initial loading direction. In the case of horizontal or nearly horizontal bending moments the trace lines drop downward near failure, indicating a shifting of the moment resistance toward the keel. This is consistent with the HALIFAX class cross section, as the two-metre long panels in the top half of the section can be expected to fail before the one-metre long panels in the bottom half. Thus, as the section approaches failure under a horizontal bending moment, one would expect the panels in the bottom half of the section to be carrying more of the load than those in the top half.

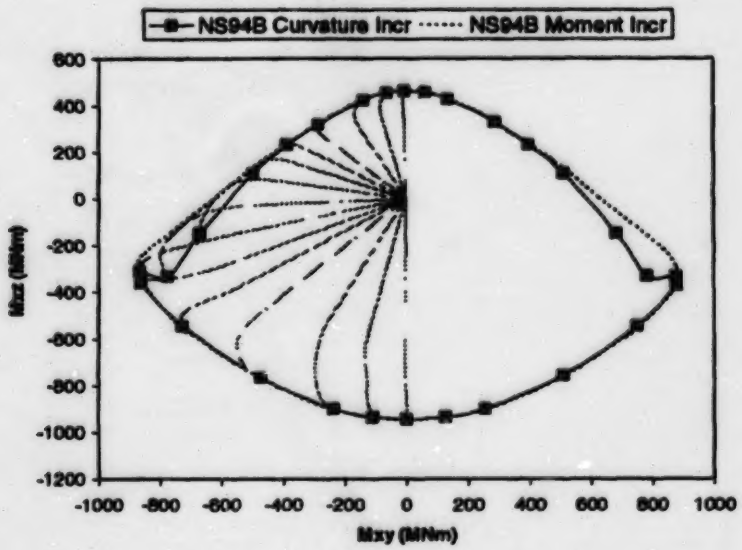


Figure 21: Bi-Axial Interaction Curves From NS94B Showing Trace Lines

When moment incrementing is used, this shifting down of the load cannot occur since the moment ratio is held constant. Instead, the curvature ratio can change, allowing for a change in the direction of the bending deformations. The interaction curves for two analyses with moment incrementing are given separately in Figures 22 and 23, respectively. The trace lines for these two cases are straight lines radiating from the starting point, confirming that the moment ratios are indeed held constant during each analysis cycle.

A question then remains as to what is the relationship between the moment incrementing and curvature incrementing bi-axial solutions. This is revealed by superimposing the moment incrementing solution on the curvature incrementing solution, as is done in Figure 21. From this it appears that the moment incrementing solution forms an envelope that just encloses the trace lines of the curvature incrementing solutions. Moreover, although the terminus of each trace line in Figure 21 represents the maximum absolute moment achievable for a given starting curvature ratio, the interaction curve inscribed through these terminal points does not mark the true collapse limit of the cross section. Excursions of the trace lines beyond the interaction curve prove that valid, pre-collapse solutions are possible in this region, and that a better demarcation of the failure limit is given by the envelope of the trace lines, i.e., by the

moment incrementing bi-axial solutions. The NS94 programs are being modified to automatically produce the correct failure envelope when curvature incrementing is used.

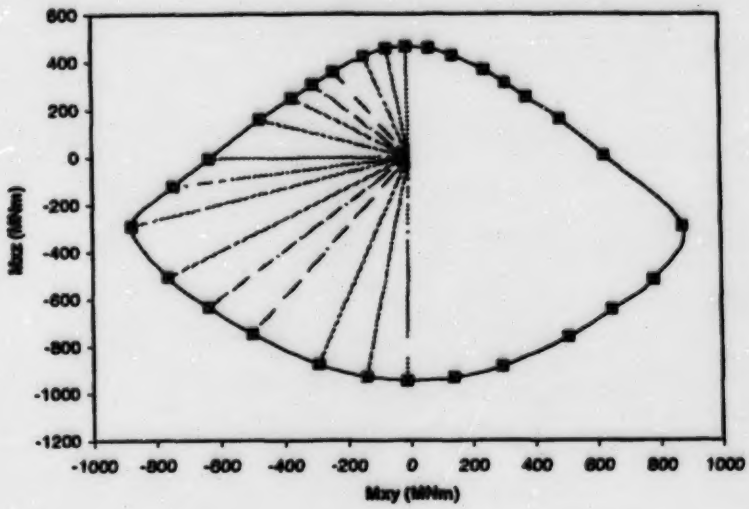


Figure 22: Trace Lines for NS94B Analysis with Bending Moment Increments

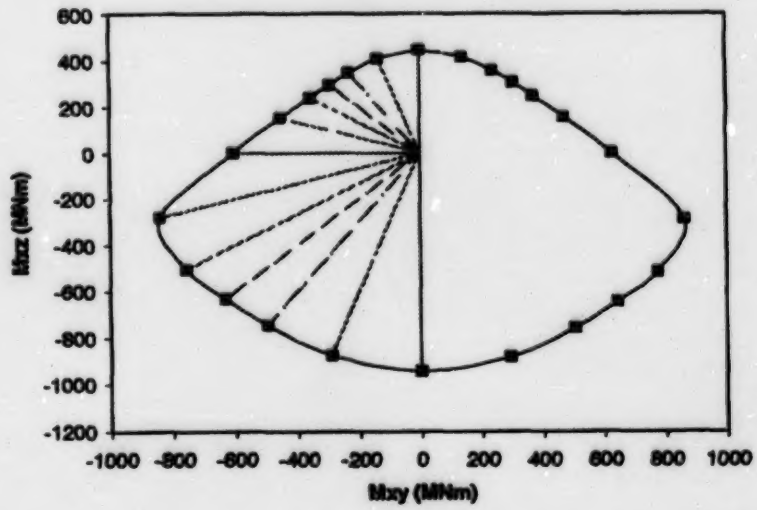


Figure 23: Trace Lines for NS94D Analysis of HALIFAX Class

3.2 ANNAPOLIS Class

Figure 24 shows a cross section generated from the MAESTRO model of an ANNAPOLIS class vessel just forward of amidships. As with the HALIFAX class, the superstructure and other discontinuous longitudinal structural units have been disabled for the purposes of the analysis. The cross section has a uniform frame spacing of 1.52 metres.

Figure 25 shows the moment-curvature plots for the hog and sag vertical bending cases. Very good agreement is obtained among the NS94A, NS94C and ULTMAT programmes, the main difference being in the post-collapse range where the results with the VAST LSC data diverge from those obtained with the NS94D LSC data. Also, slightly higher sag ultimate strengths are obtained with the NS94D database than with the VAST database, though this trend does not carry over to the hog strengths. In contrast to the HALIFAX class, the ANNAPOLIS class's hog strength is only very slightly higher than its sag strength, and the hog and sag responses show about equal tendency to collapse.

Figure 26 shows interaction curves obtained with NS94B and NS94D. The two NS94B curves (using NS94D and VAST LSC databases) were both calculated using curvature incrementing as the default. Reasonably good agreement among the three curves is obtained. Evidently, none of the discrepancies between the moment and curvature incrementing that occurred with the HALIFAX model appear here. Because the model has a uniform frame spacing, the 'shifting down' effect in the horizontal bending neutral axis is less likely to occur, at least to the extent of altering the interaction curve.

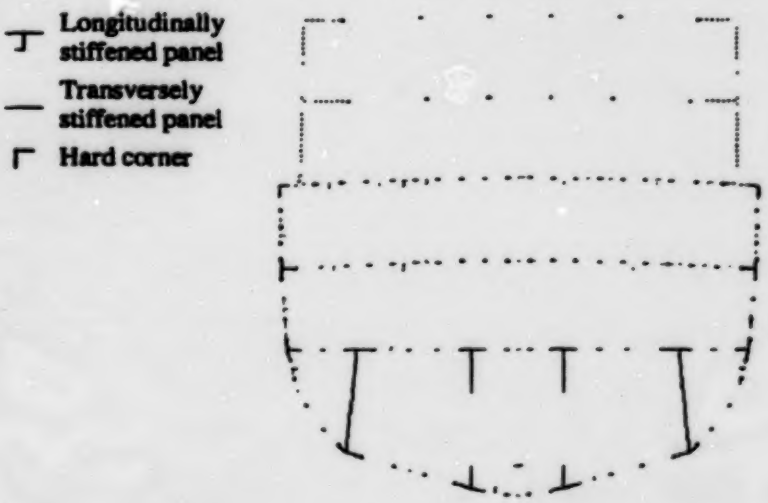


Figure 24: Cross Sectional Model of an ANNAPOLIS Class Vessel Near Amidships

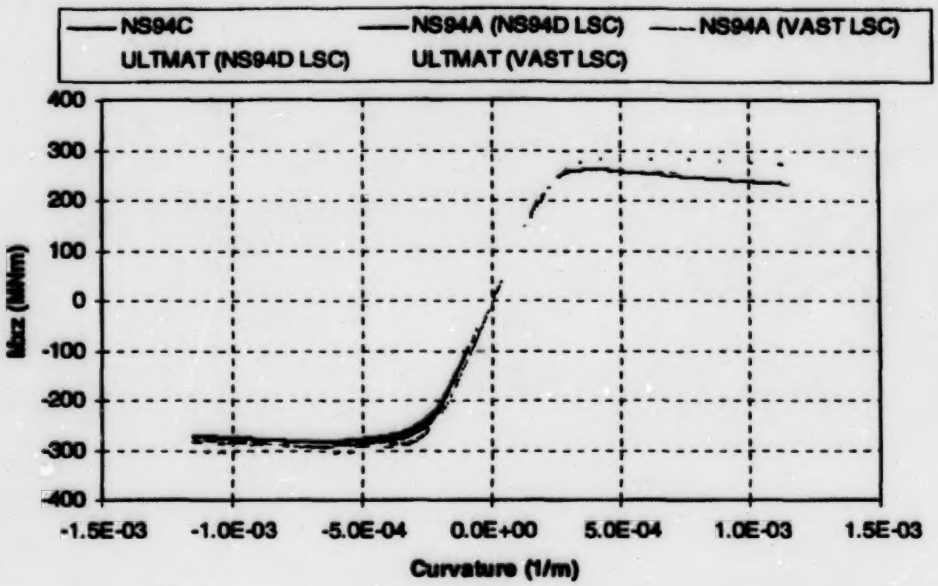


Figure 25: Vertical Moment-Curvature Plots for the ANNAPOLIS Class

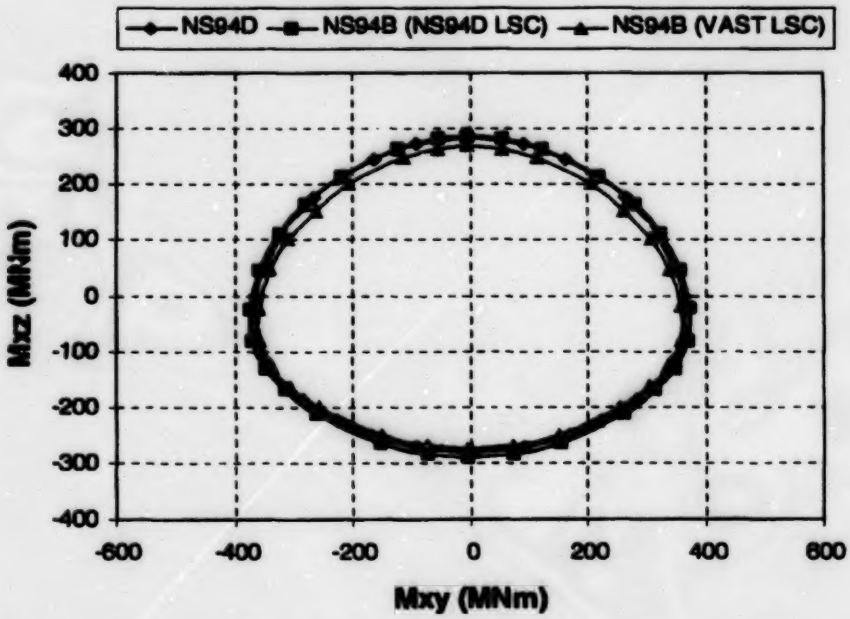


Figure 26: Bi-Axial Interaction Curves for the ANNAPOLIS Class near Amidships

3.3 Proposed ALSC Configuration

Figure 27 shows a cross-sectional model generated from a MAESTRO section of the proposed ALSC vessel. The dimensions and scantlings were obtained from the preliminary, notional, design data recently made available to DREA. At this stage of the project, the ALSC vessel is double hulled, with main frames spaced at 2.5 m and intermediate frames spaced at 0.417 m. The hull is longitudinally stiffened, mostly with bulb sections. All of the structure shown is continuous, with the uppermost structural units forming a flight deck supported above the main deck.

The intermediate transverse frames are 280×11 mm bulb sections in the hull and 160×8 mm bulb sections in the topside structure, making them similar in size to the majority of the longitudinal stiffeners. Thus, for the purposes of ultimate strength analysis they cannot be considered rigid, and should be included in the sectional model as transversely stiffened panel units. The main frames, spaced at 2.5 m, are much larger and can be considered rigid, and so this length is used as the fundamental length of all the structural units. At present, ULTSAS cannot properly model the buckling behaviour of transversely stiffened panels, due to a lack of load-shortening curves for this type of unit in the databases. A further deficiency is that the transversely stiffened panels erroneously appear in the ALSC cross section as 'hard corner' units extending down the side shells. This is a result of the way ULTSAS is interpreting the MAESTRO model. Both deficiencies are being addressed in the follow-up development occurring under the ISSMM project. As hard corners, these panels they are much too strong in compression, and thus, for reasons of conservatism, these units were disabled in the analysis.

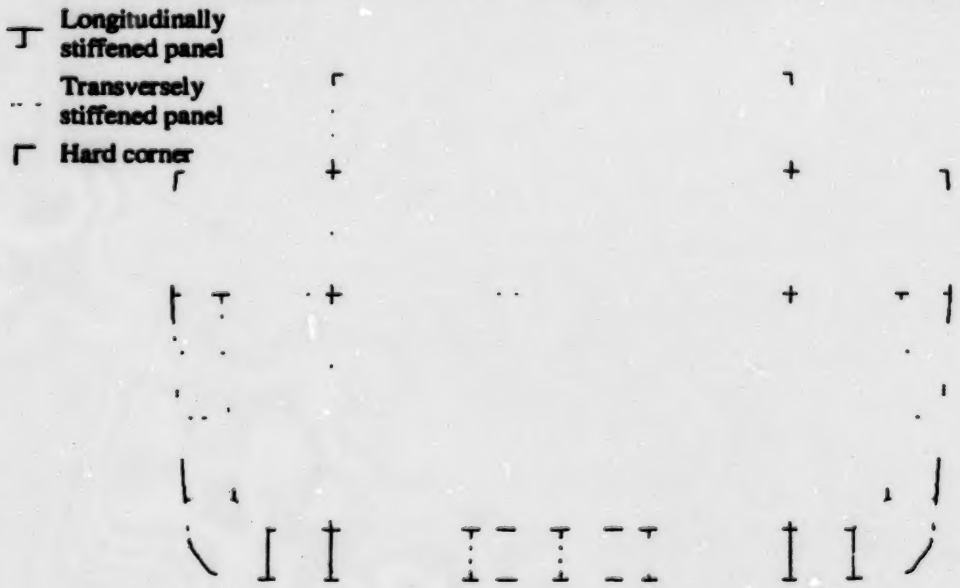


Figure 27: Cross Sectional Model for the Proposed ALSC

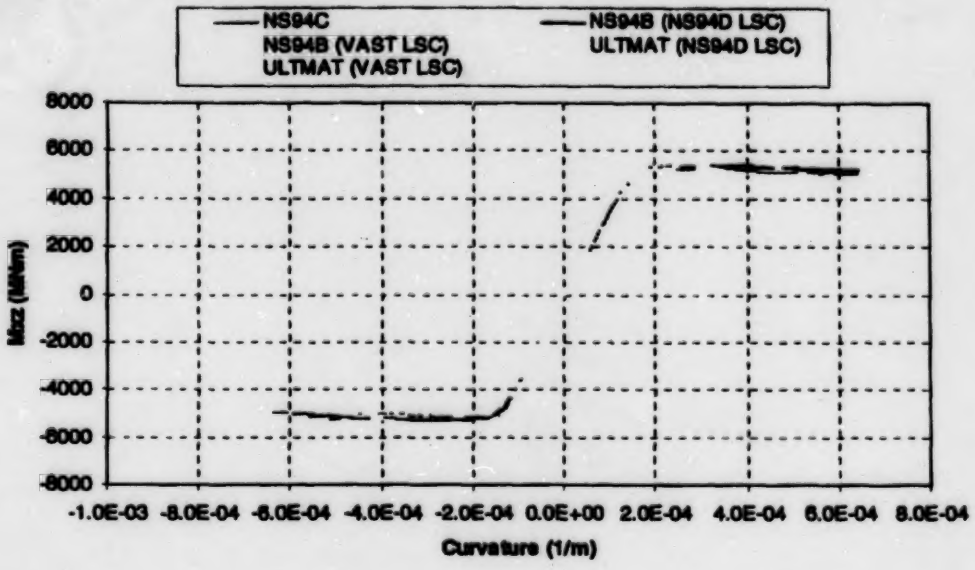


Figure 28: Vertical Moment-Curvature Plots for Proposed ALSC Section

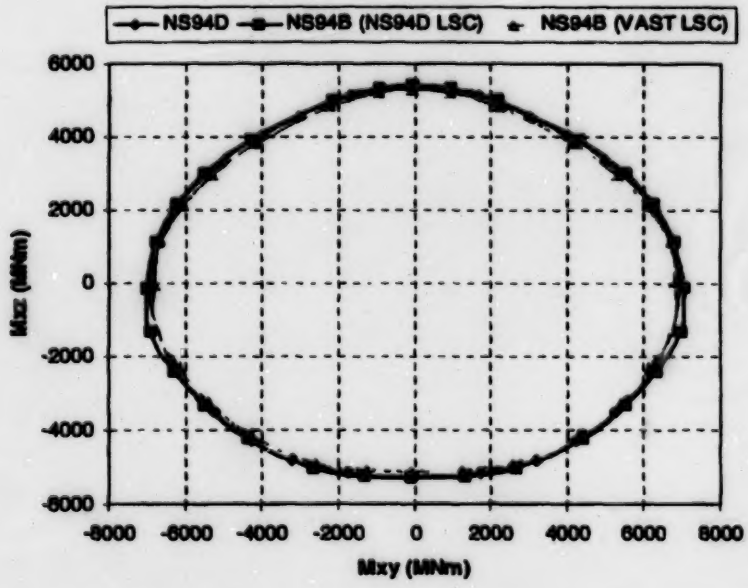


Figure 29: Bi-Axial Interaction Curves for Proposed ALSC Section

Another approximation arises from having bulb stiffeners in the cross section. ULTSAS only recognises T-sections at present; when the cross section is generated from the MAESTRO model the bulb sections are automatically converted into T-sections with equivalent area and moment properties. But this equivalence is not entirely satisfactory, since the buckling behaviour of 'equivalent' bulb- and T-stiffened panels may not be the same.

Figure 28 gives the moment-curvature plots for hog and sag vertical bending conditions produced with four different analysis options. This time, NS94B was used instead of NS94A, though there is very little difference in the results. Close agreement between NS94B and NS94C is obtained throughout, with ULTMAT producing somewhat higher estimates of the ultimate moment in both hog and sag.

Interaction curves for the ALSC are shown in Figure 29. Excellent agreement is obtained between NS94B- and NS94D-generated curves. As with the Nipigon analysis, the two NS94B analyses (for NS94D and VAST databases) were performed with curvature incrementing as the default but with no visible degradation in the results. From the Nipigon and ALSC results, it appears that there is no substantial difference between using either moment or curvature incrementing to compute the interaction curves with sections of uniform frame spacing.

4. Summary and Recommendations

This Memorandum has described the operation and application of DREA's ultimate strength analysis suite ULTSAS. It was demonstrated that this suite of codes has significantly increased DREA's ability to perform timely ultimate strength assessments of Canadian warships. By way of example, the three cross sections presented in Section 3 were all generated and analysed within an hour. However, considerably more effort was put into comparing and checking the results for inclusion in this study.

Based on the results obtained for three Canadian warships, several recommendations can be made on the correct use and future improvement of the ULTSAS.

1. For hog and sag hull-girder bending analysis, ULTMAT, NS94A, NS94B and NS94C are reliable and give comparable results in the test problems presented here.

2. Results obtained with using the NS94D generic and the VAST load-shortening curve databases are very similar except in the post-buckling range, where the VAST LSC tends to produce higher residual strengths. Which LSC database is used makes little difference to the predicted ultimate bending moments.

3. NS94D is the most reliable for generating bi-axial interaction curves. NS94B is also reliable when the structural units in the cross section are of uniform length. However, it is recommended that moment incrementing be made the default for NS94B when calculating interaction curves.

4. The implementation of transversely stiffened panels should be completed so that ship structures with intermediate framing, such as the ALSC can be properly analysed. Although the program currently allows this type of structural unit to be defined in the cross-section, no meaningful load-shortening curves are provided with which to perform an analysis.

5. The beam database should be expanded to include angle and bulb sections.

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List of symbols/abbreviations/acronyms/initialisms

ALSC	Afloat Logistics Support Capability
DND	Department of National Defence
DREA	Defence Research Establishment Atlantic
DERA	Defence Evaluation and Research Agency (UK)
FABSTRAN	Frame and Beam Static and Transient Response Analysis
FE	Finite element
ISSMM	Improved Ship Structure Maintenance and Management
IST	ISSMM Software Tool
LSC	Load-shortening curve
MAESTRO	Method for Analysis Evaluation and Structural Optimisation
MGDSA	Maestro Graphics Detail Stress Analysis
ULTSAS	Ultimate Strength Analysis Suite

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4 AUTHORS (Last name, first name, middle initial If military, show rank, e g Doe, Maj. John E)

Smith, M.J.; Pegg, N.G.

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An automated approach to ultimate strength assessment of ships using DREA's ultimate strength analysis suite is described. The analysis suite improves the ability to perform timely ultimate strength assessments of warships by providing access to UK and Canadian analysis codes and databases under a single user interface. The interface also allows for automatic cross-sectional model generation from three-dimensional ship finite element models with the MGDSA programme. A step-by-step description of the analysis options and procedures is provided, from the generation of sectional models to the viewing of results. Ultimate strength results obtained with the suite are presented and compared for three Canadian vessels. Based on these results, recommendations are made for the most effective use of the analysis suite and for its future improvement.

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Longitudinal strength
Idealised structural unit method
Moment-curvature
Bi-axial strength
Load shortening curve

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